CHAPTER 5

Summary and scope of future work

5.1 Summary

Fed-batch fermentation processes are in which the substrate(s) is added continuously to an otherwise batch operation. The controlled addition of the substrate is essential to achieve maximum production of desired product for such type of fermentation processes. The problem of determining the optimal substrate feed rate profile (as a function of time) is a singular control problem. Since the process is dynamic, the problem falls under realm of calculus of variations. The Pontyragin's Maximum principle fails to yield complete solution for problems linear in control variable and the singular control theory has to be used. In these conventional techniques the knowledge of the kinetics of the process is essential. Furthermore the solution techniques reported in the literature are problem specific.

A novel application of use of neural networks in optimization of fed-batch fermentation is reported in this work. In this approach, the optimization is achieved using only sampled data system and the knowledge of detailed kinetic model is not at all necessary. The BPNN neural network known for its simplicity and excellent ability of nonlinear function approximation is used as the tool to simulation.

The approach reported in this work is based on developing a BPNN model using the state variable data available at regular time intervals. Data is collected either from the dynamic equations or from the experimental results and used for training the NN.

The problem of determining the optimal feed rate is formulated as that of determining the feed rate at each time interval, and thereby generating the optimal feeding policy for entire duration of the fermentation The optimization problem formulated using discretization principle now becomes a problem in calculus unlike original variational calculus problem and is achieved with General Reduced Gradient Algorithm

Apart optimization model gives valuable information regarding contribution of feed, volume and the concentration of the species to a product formation or the concentration of any other species In addition, it can also be used as dynamic simulator of the process, particularly where the kinetics is not known

First, processes for which analytical (Single cell protein growth) and numerical (r-DNA protein production) solutions are known using singular control theory are considered The optimal feeding policies obtained using neural net model of the process are compared with the known optimal solutions in order to demonstrate the applicability of the algorithm developed in this work The algorithm is then applied for the process in which optimal solutions are not known (Penicillin production and Invertase production)

The time extented data is found more effective in training of the net, empowering it with extrapolation capabilities In the cases of lower dimensioned systems where analytical solutions are known the optimal feed policies show good pattern recognizing characteristics of the trained net In the optimization of higher dimensional systems different initial guesses converge to different optimal policies though maintaining accurate specific growth and metabolic production rate pattern prediction Here we considered the system of production of r-DNA protein (Case II) The ability of neural net is demonstrated to mimic a higher dimensional system for optimization of invertase production The experimental data reported in the literature is used for training BPNN The BPNN model are thus found to be suitable for predicting the dynamics of the fed-batch fermentation processes as well as for determining the feeding strategies It can be expected that the discontinuous profile obtained using BPNN will not satisfy all the optimality conditions posed by singular control theory As a result, discrete feed profile may be "suboptimal" when compared with that which in principle could be obtained using singular control theory Therefore, it is possible to further refine the BPNN generated policy using singular control

The case II with hybrid approach is found to give the initial guesses for the earlier optimal policies, converging in some local optimals, whereas the BPNN optimals are predicting close to true optimum The optimal policies generated, although not "true" optimal in framework of singular theory are easy to implement and can also be used as initial guess of the "true" optimal

Although the algorithm is developed for fed-batch fermenters , it can be adopted for chemical processes like semi-batch polymerization reactors

5 2 Scope of future work

The approach demonstrated here has not been reported earlier in the literature Although the optimal feeding policies given by BPNN match well with "true" optimum , there is a need for further improvement of the policies Some of the possible approaches that needs to be considered are a) the BPNN configuration and training b) usage of other types of networks The parameters of the BPNN, *i e*, the total number of iterations, the number of hidden nodes and hidden layers, the type of neuron used can be varied and the best set of parameters for training can be estimated The power of generalization imbibed in the Hopfield network can be utilized in modeling, optimization and control of fermentation processes

Our approach can be extended for multivariable optimization of fed-batch processes In this work the optimal profile of carbon ("C") feeding is worked out Nitrogen ("N") feeding can also be optimized, along with other variables of the system This multivariable optimization approach is appropriate for the system of penicillin production

Ultimate test to the ability of BPNN can be the modeling and optimization of the system where only the industrial data is available The unsolved problem of adaptive control, the online optimization of batch/fed-batch processes can also be encountered